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Perspectives of solar cooling in view of the developments in the air-conditioning sector

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Abstract

Changes in the standards of thermal comfort in the urban microclimate and in the capital cost of air-conditioning equipment have drastically increased the energy consumption in the building sector over the last decade. At the same time, the integration of renewable energy systems, mainly active solar ones, in buildings has been an area of intense research over the last 30 years. This has also been the case in the field of solar refrigeration, mainly in the field of sorption systems. The analysis discussed in the paper is focused on the state of the art of thermal solar systems use and on the possibilities of combining those with state of the art technologies in sorption refrigeration, in order to cover the cooling demand of residential and commercial buildings. This was done by assessing the available solar and refrigeration technologies as well as by highlighting the situation in the building market, as this is still the dominant factor for the propagation of such systems.

Contents

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1. Introduction

Peaks in electricity demand occur more frequently during the summer period in recent years in most developed countries, because of the increasing use of air-conditioning. The reasons for this lie in higher thermal comfort expectations, in lower initial costs for air-conditioning equipment and in the heat island effect in urban areas, which leads to microclimatic changes. On the other hand, the close coincidence of the maximum insolation with both the cooling loads and the peak electricity demand indicates that solar assisted refrigeration may be an interesting option to handle successfully the issue of reducing peak electricity demand due to air-conditioning. Furthermore, the solar thermal market has gained momentum in Europe since the mid-1990s, leading to a satisfactory propagation of hot water systems, which may be used for solar cooling purposes. Finally, solar assisted refrigeration appears to be a promising alternative to the conventional electrical driven air-conditioning units also from an environmental point of view, since it results in decreased CO_2 emissions and, in the case of the prevailing solar cooling technologies, in the elimination of CFCs and HCFCs. The latter has become a major aim of the European Union’s policy, as it will be discussed in section 2, and it is expected to influence the developments in the air-conditioning sector significantly.

1.1. Growing air-conditioning demand in the urban environment

Final energy consumption in buildings in the EU reaches approximately 385.6 Mtoe, which represents about 40% of the total energy consumption. This energy consumption means that the building sector is responsible for about 20% of the total CO_2 emissions [1]. Although in many countries the primary energy consumption of buildings is being reduced because of the effective energy conservation measures adapted, this refers mainly to the heating loads. In Southern Europe, but recently also in Central and Northern Europe, the primary energy consumption continues to increase, mainly due to the propagation of air-conditioning appliances [2]. This growing demand is being re-enforced by the urban heat island effect, which results in

higher air temperatures in densely built cities, enhancing the demand for air-conditioning in commercial and residential buildings and consequently also the primary energy consumption.

Studies in Southern Europe, and particularly in Greece, demonstrated that, for a representative building in the central Athens area, the cooling load almost doubles due to the urban heat island effect for indoor temperatures of 26 °C. Peak electricity loads may even treble if an indoor temperature of 19 °C is reached [3]. At the same time, the COP value of the air-conditioning units is reduced by up to 25% due to the higher ambient air and surface temperatures. The extended use of air-conditioners, mainly of split-unit devices, enhances the street canyon phenomena, a major factor in the development of the heat island in densely built urban areas. As the A/C units are usually suspended on the buildings' facades, they constitute emission points of rejected heat. The rejected heat enhances, on a micro scale level, the street canyon effect increasing even more the cooling demand of the buildings and at the same time further reduces the COP of the air-conditioners, thus creating a vicious circle in terms of cooling and electricity demand [4]. Airborne and land-based measurements carried out in Thessaloniki, Greece have verified the heat island imposed temperature distributions, indicating temperature differences across the city of up to 8 °C, whilst in some 'hot-spots' these differences exceeded 10 °C [5].

As a result of these developments, room air-conditioners sales, i.e. split-units only, increased dramatically. In Greece during the last decade, they grew from 76,000 units in 1990 to more than 200,000 units in 2000. About 42% of the sales involve units of 9,000 BTU/h, 31% of 12,000 BTU/h, 15% of 18,000 BTU/h and 12% of 24,000 BTU/h [6].

The total installed capacity of split unit air-conditioners is estimated to more than 3,500 MW, while approximately 200 MW are installed every year. Similar developments can be monitored with respect to central or semi-central units: their capacity is estimated to be more than 1,500 MW with an annual growth of about 250 MW, considering only the last five years statistics [6].

The development in the Southern Europe is in line with the Greek example as can be seen from the data presented in Table 1. The data demonstrate the high proliferation of room air-conditioners and the vast effect of them on the energy system of each country. According to the EERAC study [7], the proliferation of

Table 1
Figures of room air conditioners in four southern European countries for the year 1996 [7]

	Sales	Total stock in use	Consumption (GWh)	Peak load contribution (GW)	CO_2 emissions (tonnes)
Greece	150,880	744,830	1,321	1.72	99,235
Italy	439,490	2,111,740	4,394	4.25	182,591
Spain	318,000	1,369,000	2,396	2.62	90,000
Portugal	45,800	322,820	613	0.46	147,538

room air-conditioners in these countries will be multiplied in the next years, adding more loads to the electricity system and resulting in higher CO_2 emissions.

1.2. The impact of air-conditioning loads on peak electricity demand

The resulting increase in electricity demand concentrated in the two or three summer months, is a dominant element. As an example, the summer peak load in Greece during the years 1999–2000 showed an annual increase of 16% or 1,163 MW, while for the years 1995–2000 the increase in peak load demand reached 3,500 MW [8,9]. The change is also demonstrated by the daily maximum demand curves, as monitored in July 1998 and 2000, depicted in Fig. 1. The additional capacity needed to cover those peaks can be obtained either by expensive generation facilities with low utilisation factor like hydroelectric plants and gas turbine plants, or by electricity imports from neighbouring countries. Moreover, in recent years the Greek electricity utility faced several times blackout situations on hot summer days, due to overburdened distribution networks. It is evident that such peaks, occurring only for a few weeks a year, cannot be covered at a reasonable cost, if one tries to apply a rational pricing system, as the investments needed in infrastructure cannot be justified. Thus, in order to face the summer load peaks, without affecting the demand side, new power generation plants should be built, close to the consumption location, i.e. the major urban areas, at a high economic and environmental cost. It is more than obvious that if the utility uses a time-dependent tariff or demand a charge to cover the additional cost of the capacities needed, the operational cost for air-conditioning would be much higher for customers. The example of California in 2000 demonstrates that there are clear limits to the increase of consumption that can be covered in a liberated energy market even when demand side management tools are applied [10].

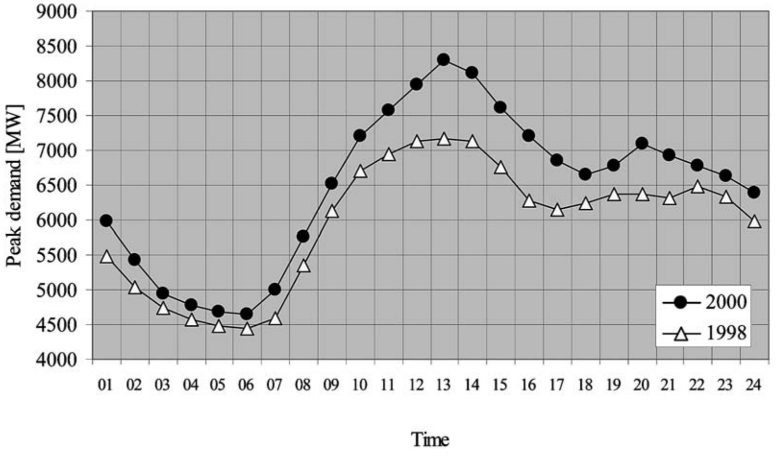

Fig. 1. Evolution of the daily peak load curve.

2. The conventional refrigerants' issue

Before the Montreal Protocol, adopted in 1987, the refrigeration and air-conditioning market was dominated by the use of CFC and HCFC refrigerants. Only in specific applications of the industrial sector was there noticeable use of other refrigerants. Fluorocarbons' popularity is based on three important properties they present:

- Zero flammability
- Low toxicity
- Good compatibility with the component materials of the A/C systems

These properties make it relatively easy to design safe refrigeration systems that can be used in locations where untrained members of the public may be in the vicinity of a refrigeration plant [11].

A new European Commission regulation on ozone layer depleting substances, Regulation 2037/2000, was implemented on 1 October 2000. This regulation treats the whole spectrum of control and phase-out schedule of the all the ozone depleting substances. Especially, for CFCs and HCFCs the key phase-out dates of the regulation are summarised in Table 2.

Given the fact that a threat to the ozone layer from CFCs and HCFCs occurs only when these substances are released into the atmosphere, the EU regulation includes specific measures aimed at minimising CFC and HCFC emissions. These focus on the following points:

- All precautionary measures practicable must be taken in order to prevent and minimise leakage.
- All fixed equipment containing more than 3 kg of CFC or HCFC refrigerant must be checked annually for leakages.
- As of 1 January 2001 no recovered CFCs can be reused and they must be

Table 2
Time table for refrigerant phase-out in the European Union [12]

1/1/2001	CFCs banned for servicing and maintaining existing systems
	Recovered CFCs must be destroyed
	HCFCs banned in new systems > 100 kW cooling capacity
1/7/2002	HCFCs banned in new systems <100 kW cooling capacity
	15% cut in supply of new HCFCs
1/1/2003	55% cut in supply of new HCFCs
1/1/2004	HCFCs banned in new reversible and heat pump systems
	70% cut in supply of new HCFCs
1/1/2008	Review of alternatives to HCFCs—ban on HCFCs for servicing and maintaining existing systems might be brought forward
	75% cut in supply of new HCFCs
1/1/2010	Virgin HCFCs banned for maintaining and servicing existing systems
	Total ban on supply of new HCFCs
1/1/2015	All HCFCs banned for servicing and maintaining existing systems

destroyed by means of an environmentally acceptable technology, usually high temperature incineration. Recovered HCFCs cannot be reused after 2015.

- All Member States must put in place schemes requiring minimum qualification levels for all service and maintenance personnel, by the end of 2001.

These new requirements will inevitably increase the cost of owning and operating refrigeration systems using HCFCs and will therefore enforce the penetration of either alternative refrigerants or alternative refrigeration technologies.

There are numerous new refrigerants on the market that have been specifically developed to address the phase out of CFCs and HCFCs.

For the long term, however, only five important global refrigerant options remain for the vapour compression cycle (as well as various non vapour compression methods including sorption, steam jet, gas cycle cooling etc. or passive and natural cooling methods):

- hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
- ammonia (R-717);
- hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
- carbon dioxide (CO_2, R-744);
- water (R-718).

None of these refrigerants is perfect. For instance, HFCs have relatively high global warming potential (GWP), ammonia is more toxic than the other options, and both ammonia and hydrocarbons are flammable. Interest in ammonia and hydrocarbons is stimulated, at least in part, by the fact that HFCs are greenhouse gases which will be, according to the Kyoto agreement, subjected to control measures. However, safety aspects also imply stringent emission controls for ammonia and hydrocarbons. Although these aspects are not covered by the Montreal Protocol, they nevertheless form criteria in the ongoing ‘environmental acceptability’ debate. Appropriate equipment design, maintenance and use can help to reduce these concerns, though at the cost of greater capital investment or lower energy efficiency. Respectively, energy efficiency research is partly encouraged by the contribution of energy production to carbon dioxide (CO_2) emissions [13]. All these aspects transform the future strategies on selection of refrigerant technologies into a delicate optimisation procedure, at least on a medium and long-term basis.

So far, the existing legislation on ozone depleting substances has placed increasing pressure on CFC and HCFC end users to start using alternative fluids and technologies. It has resulted in the extended use of HFCs, which are highly attractive for cooling applications. Prior to 1990 there was very little use of HFCs in Europe. This resulted in HFC-23, released as a by-product of HCFC-22 production, being the only significant atmospheric emission of HFCs. Since 1990, however, there has been a significant growth in the market for HFCs because, as mentioned above, they provide effective alternatives to CFC and HCFC. The favourable properties of zero flammability and low toxicity, displayed by most HFCs, make them a popular alternative, both in existing and new systems. Furthermore, they have zero ozone depletion

potential (ODP). Despite the fact that all pure HFCs and most HFC blends require synthetic lubricating oils, instead of the more conventional mineral oils used with CFCs and HCFCs, the use of HFCs to replace CFC or HCFC in refrigeration plants is currently the option with the lowest cost for many users.

On the other hand, whilst they have zero ODP, HFCs have a significant global warming potential (GWP). This is typically in the range of 1,000–3,000 times the GWP of CO_2. At the 1997 Kyoto meeting, HFCs were included as one of six global warming gases being targeted for emission reductions. It is of high interest to note that in 1995 the air-conditioning and refrigeration market was responsible for HCF emissions of 4.3 Mt of CO_2 equivalent, a figure corresponding to about 11% of the total HCF emissions. This figure is expected to increase to 28.2 Mt of CO_2 equivalent in the year 2010 equalling approximately 43% of the total HCF emissions [11].

Considering the alternative refrigeration technologies, one cannot fail to mention their lower efficiency compared to the conventional vapour compression systems. That is why the possibility of partially solar powered cooling using alternative technologies like sorption or steam ejector cooling, can counterbalance their higher final energy consumption and set them as the most environmental friendly cooling option from every aspect, including ozone depletion potential, global warming potential and primary energy consumption.

3. Solar refrigeration technologies

Solar energy can be transformed either to electricity or to heat allowing, in theory, any refrigeration technology to be driven by it. Still, several constraints concerning both the quality and the quantity of solar energy limit the potential of solar driven, or even solar assisted refrigeration technologies. Keeping in mind the characteristics of solar electricity and thermo-mechanical systems, and also for reasons of brevity, they will be discussed only to a limited extent.

3.1. Electrical and thermo-mechanical systems

The electrically driven systems are characterised by the limited useful power that can be achieved by solar means, and also by their fairly high initial cost. The main types that can be utilised for solar refrigeration are:

- the photovoltaic Peltier systems, commercially available for ‘spot’ cooling of electronic components and systems,
- the photovoltaic vapour compression systems, an attractive option for small refrigeration units, like vaccine storage, in places where electricity is not available, and
- the photovoltaic evaporative cooling.

The latter is based on the well-known low energy cooling technology, which has been applied for many years, especially in hot and dry climates.

Solar energy utilisation refers to the modulation of a solar photovoltaic array in order to provide part or all of the electricity needed to operate a system. Evaporative cooling should be combined with an additional cooling device, in order to cope with large cooling loads. This could be a desiccant or a conventional vapour compression system. In any case, evaporative cooling is best suited for hot and humid climates and in areas where the availability and the cost of the water allow its operation. It presupposes a significant drop in the initial cost of photovoltaic elements. There is also the option of the photovoltaic Stirling driven engine, but significant development is needed for this system to become a practical alternative.

The option of utilising thermo-mechanical processes to produce refrigeration is, at least from the thermodynamic aspect, a sound one. There are, however, still many problems to cope with in order to achieve acceptable efficiencies of the various processes, like the ones based on the Vuilleumier and the Rankine cycle, or the steam jet cycle.

3.2. Solar sorption refrigeration technologies

Considering the problem of peak load increase during summer months caused by electrically driven A/C systems, and the time correlation between insolation and cooling demand, the heat driven—solar assisted—chillers seem to have an excellent potential in the space air-conditioning business, albeit that so far they are not really a competitive alternative to the conventional vapour compression chillers. Solar sorption refrigeration technologies are, hence, the prevailing option for the utilisation of solar energy in air-conditioning. This applies to adsorption, absorption and desiccant cooling.

Sorption systems are referring either to open or closed cycles. Open cycles are mainly desiccant systems, while closed cycles are adsorption or absorption systems. In desiccant systems, sorbents are used for the dehumidification of the incoming air, which in that sense is not a refrigeration process, though it is certainly part of air-conditioning. It falls therefore beyond the scope of this paper.

Adsorption involves the use of solids for removing substances from either gaseous or liquid solutions. The process of adsorption concerns separation of a substance from one phase, accompanied by its accumulation or concentration on the surface of another. On the other hand, absorption is the process in which material transferred from one phase to another, (e.g. liquid) interpenetrates the second phase to form a solution. Both phenomena of absorption and adsorption are used to provide thermal compression of the refrigerant instead of mechanical compression in the case of vapour compression cooling systems.

Absorption systems are the oldest and most common heat driven systems. On the low-pressure side, an evaporative refrigerant is absorbed by the absorbent formulating a weak absorbent solution. The weak solution is directed to the generator where the pressurisation takes place by desorption of the refrigerant. The refrigerant then undergoes a common cooling cycle, while the weak solution is directed to the absorber and the cycle is repeated. Adsorption systems are based on a physical or chemical reaction process in which the molecules of one substance are adsorbed on

the internal surface of another substance. Evaporation and adsorption of a refrigerant produce a useful cooling effect. Regeneration of the sorption material is achieved by hot water. The main differences between adsorption and absorption are located in the nature of the sorbent and the duration of the sorption cycle. The general operating principal of solar closed cycle sorption refrigerator is presented in Fig. 2.

The sorption refrigerator includes one or several reactors, i.e. regenerator(s), absorber(s), adsorber(s), generator(s) etc., depending on the specific cycle and the sorption pair, and of course the condenser and the evaporator, which exchange refrigerant vapour with the thermal compressor. In principle, a sorption cycle is a four temperature cycle, but the two heat quantities Q_{SO} and Q_{CO}, commonly rejected to the intermediate temperatures T_{SO} and T_{CO} respectively, are transferred to the same heat sink. In technical terms, the heat is removed from a cold water stream in a closed loop, passing serially from the generator, the condenser and the cooling tower. Thus, it is assumed that $T_{SO} = T_{CO}$ and the cycle is considered to be a three temperature cycle. The heat Q_{GE} is supplied by the heat source (solar collectors) at temperature T_{GE} to the thermal compressor (sorption system), where it induces desorption of the refrigerant vapour at the condenser pressure. The vapour is liquefied in the condenser at the intermediate temperature T_{CO}. When the sorption system is cooled down back to the intermediate temperature T_{SO}, it reabsorbs vapour, which is produced by the vaporisation of the liquefied refrigerant in the evaporator. The vaporisation heat Q_{EV} derives from the cooling space, through the chilled water circulation. The coefficient of performance of a sorption refrigerator is expressed as the amount of cooling delivered (cold produced) divided by the amount of the required heat input. COP = (Cooling Delivered/Heat Input Required)

$$\mathrm{COP} = \frac{Q_{\mathrm{EV}}}{Q_{\mathrm{GE}}} \tag{1}$$

where, Q_{EV} denotes the heat removed from the cooled space; and Q_{GE} denotes the heat derived from the heat source to the generator (desorber).

The reversible COP, which is the maximum COP of a sorption refrigerator, is equal to the efficiency of a Carnot thermal engine driven by Q_{GE} and delivers the

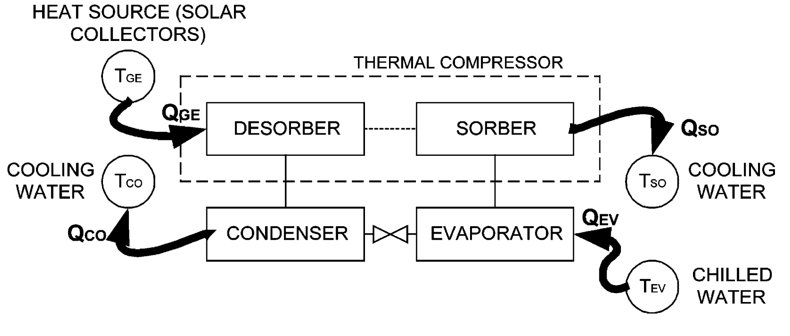

Fig. 2. Schematic representation of a sorption refrigerator.

working output to a Carnot refrigerator removing Q_{EV} from the cooling space. Thus, the reversible COP_{rev} (COP_{Carnot}) is equal to

$$COP_{rev} = \left(1-\frac{T_{CO}}{T_{GE}}\right)\left(\frac{T_{EV}}{T_{CO}-T_{EV}}\right) \tag{2}$$

where, T_{CO} denotes the temperature of the cooling water that cools down the condenser and the sorber, T_{GE} denotes the temperature in the generator (temperature of heat derived by the heat source) and T_{EV} denotes the temperature of the chilling water.

The ratio of COP to the COP_{rev} is the thermodynamic efficiency η, of the sorption refrigerator

$$\eta = \frac{COP}{COP_{rev}}. \tag{3}$$

Treating the most important points that characterise solar sorption systems, one can highlight the influence of the regenerative temperature, which is the temperature of the heat derived from the solar collectors, in the COP of the cooling machines. Thus, it becomes evident that the overall efficiency of a solar sorption cooling technology, which has a global optimum for certain conditions, depends on the type of the collector, the solar radiation and the evaporator temperature. Current research on solar sorption cooling systems is focusing both on increasing the temperature output of the solar collectors and decreasing the temperature input of the sorption chillers in order to increase the overall COP.

3.2.1. Absorption systems

Two major absorption systems can be met in solar cooling: the lithium bromide–water and the water–ammonia absorption cycles.

The basic lithium bromide–water (LiBr) absorption cycle has been in use in refrigeration applications since the 1940s. Its key characteristics are determined by the pressure–temperature concentration (PTX) equilibrium chart, the solution cycles, the individual components and the chemical additives. Its functional performance is mainly characterised by the partial load operation and the particularities of maintenance of the system. In this cycle, LiBr is the absorbent and water is the refrigerant. The output of a LiBr system can be as low as 4 ^{o}C. These absorption systems are categorised by the number of times the solution is heated to produce refrigerant vapours, referred to as the number of effects. Fig. 3 shows a typical single effect solar driven LiBr–water absorption refrigeration system.

Most LiBr absorption systems are single or double effect systems. A single-effect system uses the heat input once, while a double-effect system uses the heat input for one deabsorption stage and the warm refrigerant vapours as the heat source for the second stage. The temperature of the heat source required to drive the high stage generator must be higher than the one used for a single effect machine. Overall, a double-effect system is preferred to a single one when there is a heat source at temperatures sufficient to power a double-stage machine. This fact, together with the

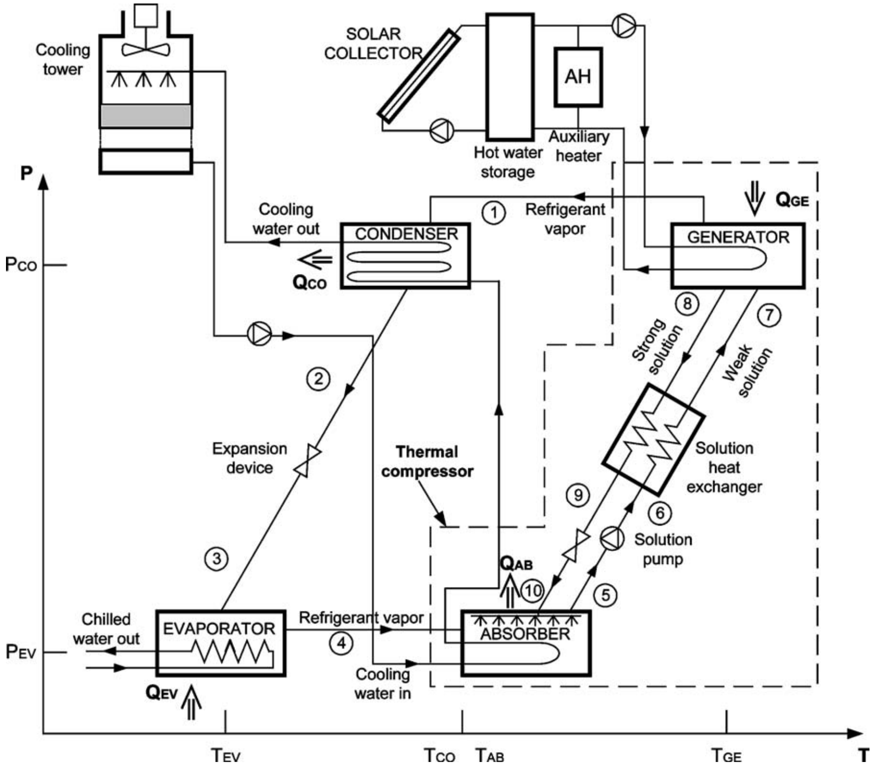

Fig. 3. Schematic of a solar driven LiBr–water single effect absorption refrigeration system.

initial cost, which is higher than the one of a single-effect machine, sets the limits for the use of solar systems combined with a LiBr absorption machine.

The second widely used refrigeration system is based on the water–ammonia absorption cycle (WAC). This system is mainly encountered in industrial applications, in chemical processes, in the food industry and in drying processes. It is also suitable for solar energy applications. In the case of a WAC, water is the absorbent and ammonia is the refrigerant (i.e. the opposite of the LiBr cycle). The cooling output in most cases is liquid ammonia, separated from the ammonia in the WAC machine, as opposed to the chilled water used in LiBr absorption systems. Due to the fact that ammonia is the refrigerant, the output of an (WAC) system can be as low as -60 °C. If the system is installed in a closed space, ventilation is required by the standards for ammonia refrigeration. WAC systems are categorised according to the number of evaporator stages. A single-stage system has one stage of evaporation/absorption, and a two-stage system has two stages of evaporation/absorption. The number of stages of evaporation can be increased in order to reach the cooling and the refrigeration temperatures required by the design parameters. WAC systems are tailor-made systems for each application. The operational principles of a WAC system are similar to those of LiBr absorption machines.

3.2.2. Adsorption systems

The main differences between absorption and adsorption sorption cooling systems lie in the nature of the sorbent, which in the latter case is a solid material, and in the duration of the cooling cycle, which is significantly longer for adsorption. The main adsorbents used for air-conditioning purposes are silica gel and zeolite, with water as refrigerant. Activated carbon/methanol systems, in use since the 1930s, can also serve for refrigeration purposes, since methanol can be cooled below 0 °C, although methanol's vaporisation enthalpy is smaller than water's. On the other hand, zeolite/water systems demand regeneration temperatures of 170 °C, while active carbon/methanol systems, and in particular the silica gel/water ones, can utilise heat at temperatures below 100 °C. As a result, and for air-conditioning applications, the most common pairing is silica gel–water.

In principle there are two broad categories of adsorption systems: continuous and intermittent, with intermittent systems being more suitable for the utilisation of solar energy since they are daily cycle systems [14]. Another structural categorisation of adsorption systems concerns the nature of the adsorption effect and particularly whether or not it is a physical phenomenon or whether or not it includes a chemical reaction. When fixed adsorbent beds are employed, which is the common practice, these cycles can be operational without moving parts other than magnetic valves. This results in low vibration, mechanical simplicity, high reliability and a very long lifetime. The use of fixed beds also results in intermittent cycle operation, with adsorbent beds changing between adsorption and desorption stages. Hence, when constant flow of vapour from the evaporator is required in order to provide continuous cooling, two or more adsorbent beds must be operated out of phase [15]. Compared to absorption, adsorption chillers are more expensive and their commercial availability is still limited. In principle, their COP is lower than that of the absorption chillers, but they can utilise heat at lower temperatures, they can thus be driven by flat plate solar collectors more efficiently. Fig. 4 shows a single stage silica gel/water adsorption chiller driven by solar energy.

Two stage cycles allow for the reduction of the adsorbent's regeneration temperature by dividing the evaporating temperature lift in two. Thus, refrigerant (water vapour) pressure rises into two progressive steps from the evaporation to the condensation level. In order to attain this objective, the introduction of two additional sorption elements is necessary [16]. An advanced, two-stage cycle comprises of six heat exchangers, namely, a condenser, an evaporator and two pairs of sorption elements. The desorption elements are heated by hot water while the adsorption elements are cooled by cooling water. Hence, an uninterrupted supply of cooling energy requires operation as a pseudo-continuous cycle, where adsorption and desorption occur concomitantly and sorption elements repeatedly switch between adsorption and desorption modes.

A two-bed continuous adsorption refrigeration system with heat recovery operation can provide continuous cooling. When the first adsorber is cooled and connected to the evaporator to get adsorption refrigeration in the evaporator and the second adsorber is heated and connected to the condenser to get heating–desorption–condensation, the condensed refrigerant liquid flows into evaporator via a flow control valve.

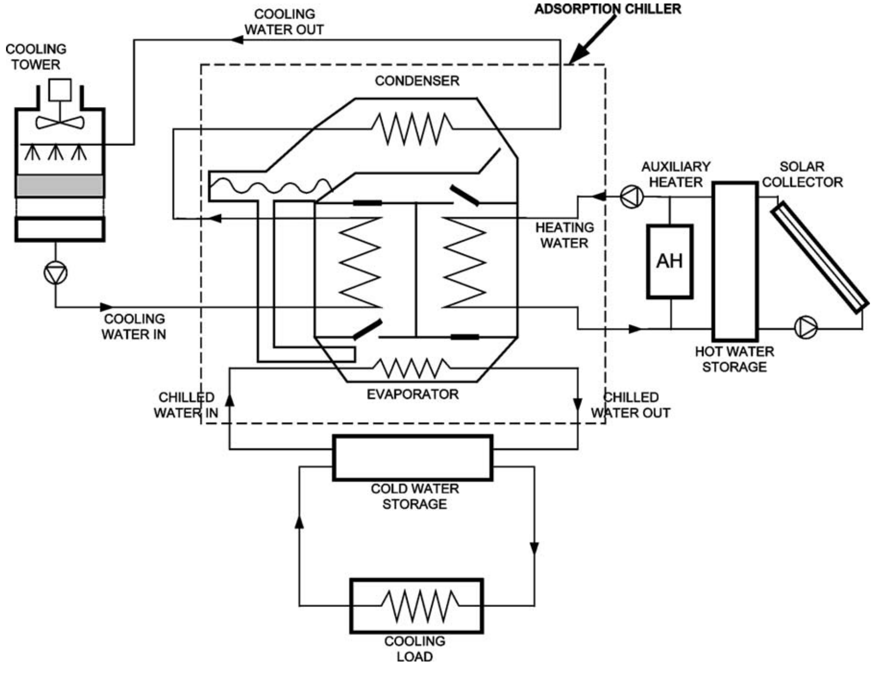

Fig. 4. Schematic of a single stage silica gel–water adsorption chiller.

The operation phase can be changed, and the go-between will be a short time heat recovery process in which two pumps drive the thermal fluid in the circuit between two adsorbers (the connection to the heater and cooler are blocked during this process). Heat recovery is important in order to increase the cycle COP; the possible heat recovery for a two adsorption bed system will be partly sensible heat and partly heat of adsorption [17].

Another option is the plate type adsorber/collector solar refrigerator. These refrigerators are usually operating with an activated carbon/methanol pair and are mainly composed of an evaporator, a condenser and a solar collector coupled to the adsorber or reactor filled with adsorbent. Often, in order to improve the collector's performance and to obtain temperatures up to 100 °C, a selective coating for the absorber surface and a polycarbonate honeycomb, such as Transparent Insulation Material (TIM) is incorporated. Solar adsorption refrigerators are mainly used for ice production.

In a typical system the adsorbent bed, which is mounted inside the solar collector, is made of aluminium plate, covered with coating material, and placed behind a single sheet of glass in an insulating case equipped with dampers on its top and bottom for cooling when adsorbing. Adsorbent (activated carbon) is placed within the aluminium plate. In order to improve the heat transfer between the front side and the adsorbent, aluminium fins are placed inside the collector in contact with the front side and the adsorbent [18].

Table 3
Main features of solar sorption refrigeration technologies[a]

	Technology			COP	Application	Input (°C)	Availability
Sorption	Absorption	LiBr–water	Single-effect	0.5–0.75	AC	80–100	C
			Double-effect	0.8–1.2	AC	100–160	C
		Water–ammonia	Single-stage	0.5	AC-R	120–150	C
			Two-stage	1.2–1.3	AC-R		C
	Adsorption	One-stage (silica gel/water)		0.3–0.7	AC	60–90	C
		Two-stage (silica gel/water)		0.35–	AC	50–75	L
		Adsorber/collector		0.10–0.5	R		C

[a] AC: air-conditioning; L: laboratory; R: refrigeration; C: commercial; D: dehumidification.

3.3. A synopsis

The main features of the possible solar refrigeration technologies, with respect to their COP, application, input needed, and stage of availability are presented in Table 3.

Combining the current trends of the available solar collectors and those on refrigeration technologies in Table 3, a correlation between the two areas can be produced. This is depicted in Fig. 5. In this collector efficiency-driving heat temperature diagram, the three most commonly used solar collectors are presented (flat plate, evacuated tube and solar air collectors) with the operating range of four prevailing (sorption cooling technologies, desiccant, adsorption and single and double effect absorption cooling). It is obvious that for desiccant cooling, either solar air or flat plate collectors

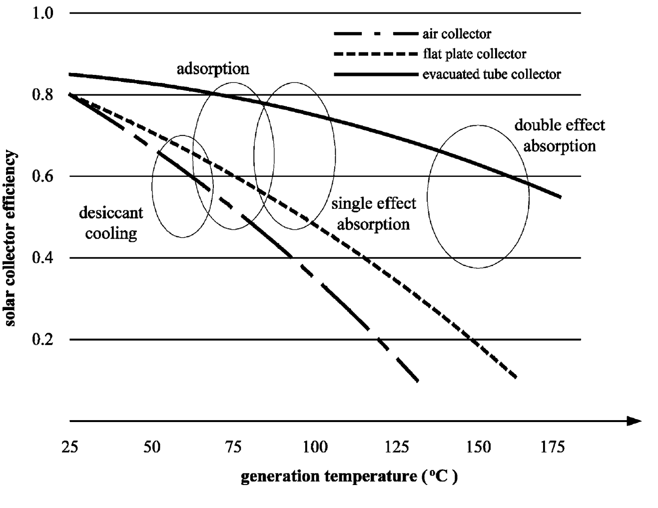

Fig. 5. Possible combinations of solar thermal and sorption refrigeration technologies (Source [19]).

can be used, while, for adsorption and single effect absorption cooling, either flat plate or evacuated tube collectors can be used. Finally, for double stage absorption cooling, only vacuum tube collectors are suitable. The recently developed CPC collectors are an additional option for sorption cooling, which can deliver also heat at high temperatures.

4. The market for solar thermal systems and its implications on solar cooling

At the end of 1999, the total installed surface of solar collectors in the EU reached 8.8 million m^2, demonstrating a 7.3% increase on the previous year. This figure is perfectly inscribed in the changing scene of the last four years, during which average annual growth reached 6%. The data on the development of annual installations also showing the participation of each type of collectors, are presented in Table 4. The presence of flat plate collectors in the market is dominant, mainly due to its low initial cost, its simple and robust technology and a performance that has improved over the last decade. This market situation should be taken into consideration when determining a strategy for promoting solar refrigeration, as it is rather difficult to try to promote more than one new, cost-implying technology at a time. On the whole, the perspectives of thermal solar energy growth in the EU remain good. Taking into consideration the efforts of each country, the surface of solar collector should reach 87 million m^2 by the year 2010, with a national distribution as presented in Table 5. This figure should be compared with European Commission targets, which, in its White Paper on renewable energies, announced 100 million m^2 installed by 2010 [20]. Projections reveal that this target is slightly behind schedule, by approximately 13 million m^2, i.e. the equivalent of one year of installations [21].

Given the fact that solar refrigeration is still, financially and technologically, not a competitive option to conventional air-conditioning systems, particular emphasis must be placed on utilising the advances already achieved in solar thermal systems in the building sector, in order to offset the initial difficulties of solar refrigeration. There are certain favourable socio-economic boundary conditions, such as the large scale building renovation projects, the creation of buyer groups for solar buildings and/or solar building products and the increasing environmental consciousness. If transformed into a flexible but effective framework of policies, they could contribute to an accelerated propagation of solar cooling systems. There are three major groups of measures that can be taken towards sustainable energy policies, as presented in Fig. 6, and solar systems are affected by at least, two of these tools: technology support programmes and economic instruments.

Some of the points that could be part of the technological policies are: industry product selection tools, development of best practices for solar buildings, guidelines for builder associations, decision guidelines for the purchase of solar buildings/products etc.

These points have to form the strategic axis of action for any measures to promote solar thermal systems if it is to become successful, because, as proven so far, the influence of research and development projects on the promotion of systems until

Table 4
Annually installed solar collectors per type and country (in thousands of m^2) [22]

	1998				1999			
	Glazed	Unglazed	Vacuum	Total	Glazed	Unglazed	Vacuum	Total
Germany	337.0	21.9	53.0	411.9	380.0	22.8	60.0	462.8
Greece	153.4	1.0	1.0	155.4	158.0	1.0	1.0	160.0
Austria	163.0	32.3	2.6	197.9	138.8	16.9	2.4	158.1
France	18.5	9.0	0.0	27.5	24.3	8.0	0.0	32.3
Italy	24.6	1.4	1.0	27.0	41.3	2.3	1.5	45.0
The Netherlands	24.4	2.2	0.0	26.6	25.7	2.0	0.0	27.7
Spain	19.6	0.0	0.0	19.6	21.0	0.0	0.0	21.0
Denmark	17.5	0.2	0.0	17.7	15.3	0.3	0.0	15.6
Sweden	7.1	2.6	0.3	10.0	8.8	2.9	0.1	11.8
Portugal	8.0	0.0	0.0	8.0	8.0	0.0	0.0	8.0
Great Britain	5.8	3.2	0.0	9.0	5.8	3.2	0.0	9.0
Belgium	2.0	0.4	0.1	2.5	2.0	0.5	0.1	2.5
Finland	0.8	0.0	0.0	0.8	1.0	0.0	0.0	1.0
Total	781.7	74.2	58.0	913.9	829.8	59.8	65.1	954.7

Table 5
Estimation of collector surfaces to be installed in Europe by the years 2005 and 2010 (in thousands of m^2) [22]

	2005	2010
Germany	17,000	55,000
Austria	5,200	10,400
Greece	4,860	9,800
Holland	—	1,360
Spain	—	4,500
Italy	—	3,000
France	770	1,450
Rest of EU		1,700
Total	27,830	87,210

now has been rather marginal [23,24]. The European Union and the Commission of the European Communities supported, in the 1990s, a series of actions concerning research and development as well as dissemination and integration [25]. It remains to be seen how the experience and knowledge obtained over these years will be utilised under the new 6th Framework Programme, launched in early 2003, in order to achieve the highest possible efficiency.

As far as the economics and legislation are concerned and beyond conventional measures like fiscal incentives, one could mention the following actions that could enforce a more environmentally conscious evaluation of solar systems: the quantification and internalisation of the environmental benefits of solar designs/technologies, the trade-off analysis of environmental issues and solar building strategies, the economic analysis and quantification of CO_2 reductions from solar buildings, and the adaptation of a common life-cycle analysis method to evaluate the alternatives [26].

5. Conclusions

Solar cooling can become a promising solution for the clean, energy thrifty and sustainable air-conditioning of urban buildings. As the demand for air-conditioning is sharply increasing in the urban environment and, considering the fact that soft technologies like passive cooling are very difficult to apply in existing buildings, the technologies discussed in this paper may provide a competitive alternative to conventional air-conditioning systems. The increasing efforts in solar refrigeration research and several advances in collateral fields, like the solar thermal sector, indicate that both the research community and the industry are aware of the high potential of this solution. The main advantages concern the reduction of peak loads for electricity utilities, the use of zero ozone depletion impact refrigerants, the decreased primary energy consumption and the decreased global warming impact.

However, and despite the progress made, there is still the necessity for a leap forward. This can only be achieved by means of an energy policy that determines

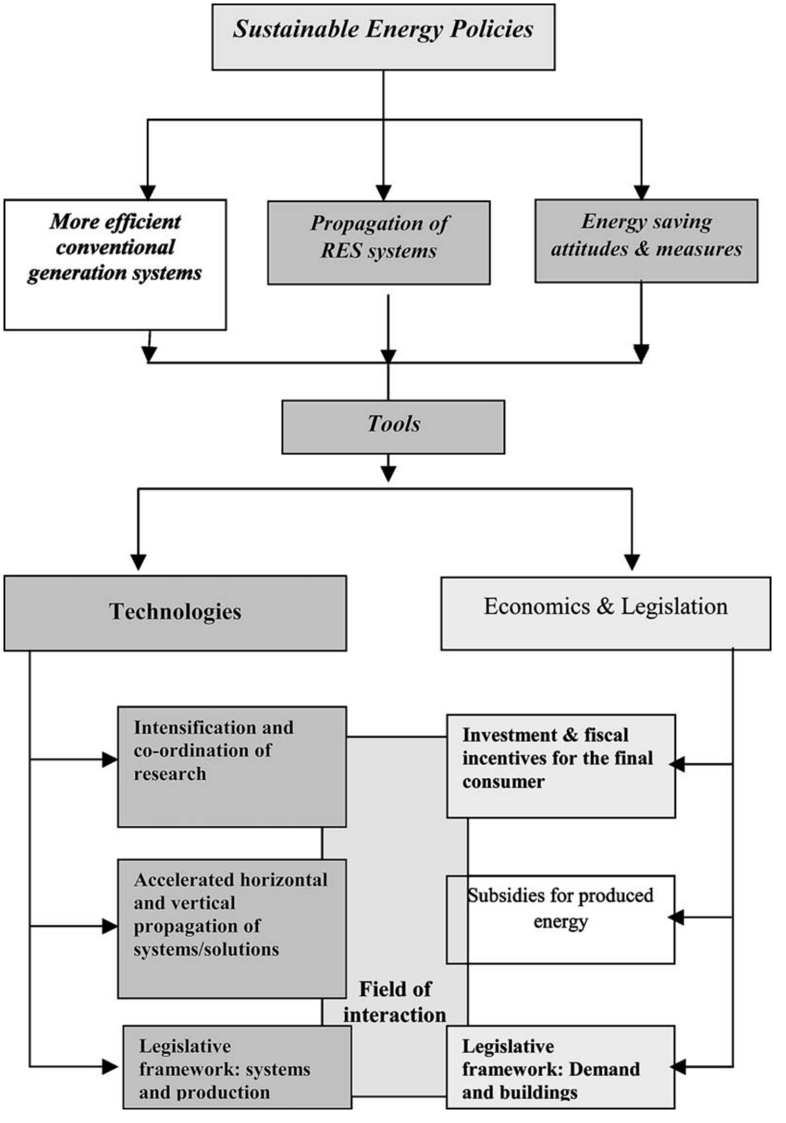

Fig. 6. Tools to implement sustainable energy policies.

and exploits the advantages of solar refrigeration. In order to fully exploit them, one needs an alternative way to make comparisons with the conventional electrically driven cooling systems, which will not be limited to the conventional energy and monetary performance. This has to include: the consideration of ozone depletion potential, global warming potential, primary energy ratio and, finally, the widely accepted method for evaluating renewable energy sources, namely life-cycle analysis. Under these perspectives the option of solar refrigeration becomes more attractive.

In addition, the disadvantage of low financial feasibility can, to a great extent, be offset if both electric and gas utilities prepare and launch demand side management actions concerning air-conditioning. Such actions would lead to a more reasonable pricing of energy, with respect to its real production cost. Thus, a strategic management program, treating the implementation of solar air-conditioning, is a priority action to verify the current and future technological, economical and social aspects and the parameters needed to be fulfilled for acceptance and wider penetration of solar energy in the air-conditioning business.

In that sense, there is still a high research demand for the utilisation of solar energy in air-conditioning systems; research mainly focused on solar collectors and, more intensely, on the sorption cooling technologies. Still, one cannot fail to notice that the optimisation of solar air-conditioning systems also concerns the cooling demand side. The cooling demand’s profile is a product of the building’s characteristics and the occupants’ behavioural patterns. Passive or natural cooling techniques have proven to be very efficient in reducing significantly the cooling load of the building and lead, thus, to more reasonably dimensioned and cost efficient refrigeration systems. The challenge, therefore, is the integration of passive and natural cooling techniques with solar refrigeration technologies.

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